Research in Free Space Optical Data Transfer at the U. S. Naval Research Laboratory

by

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ABSTRACT

In this paper, a review of the progress and initiatives in free space optical data transfer and communications at the Naval Research Laboratory is presented. NRL has been investing in research and development in optical communications and laser ranging, both conventional, and advanced. Efforts include developing amplifiers and components for lasers to be used in long range, one-way and retro-reflected links. NRL has been developing Multiple Quantum Well retromodulators for space-based and terrestrial-based applications as well. These include spacecraft-to-spacecraft data links for navigation and communications, intra-bus networks on spacecraft, and optical tagging. Terrestrial applications in the eyesafe regime have led to additional studies in how the atmosphere affects one-way and modulated retroreflected signals in the maritime environment, in particular. New results from retro-diversity experiments, over-the-water propagation studies, and field tests are discussed.

1. INTRODUCTION

The Naval Research Laboratory (NRL) has been investing in advanced optical data transfer techniques since the 1970's. Recent studies include efforts in optical communications and satellite laser ranging, both conventional and advanced. At this time, NRL has two ongoing 6.2 programs in optical communications and tagging. These programs address high data rate links – tens of gigabits per second (Gbps) – and passive optical terminals based on Multiple Quantum Well (MQW) retromodulators which operate at megabits per second (Mbps) [1-3]. NRL also supports a dual interrogator program for retromodulator data links administered through the Office of Naval Research (ONR), as well as perform as SBIR advisors for advanced optical communications applications serving Navy needs. NRL's goals for these programs are to demonstrate feasibility and conduct engineering science in device development and atmospheric effects as they pertain to data links in the near infrared. To achieve these goals, investigations are ongoing in device and technology development, in techniques, such as forward adaptive error correction, and in atmospheric propagation. Figure 1 shows a break out of technologies and techniques explored as a function of data rate. This paper summarizes progress in these areas at NRL.

It should be noted that the NRL has a satellite laser ranging site located on the east coast which offers a 1 meter telescope, 3 Watt 1.06 micron laser which has a pulse repetition frequency of 10 Hz. This paper will not address progress at the facility but details are available in the references [4, 5].

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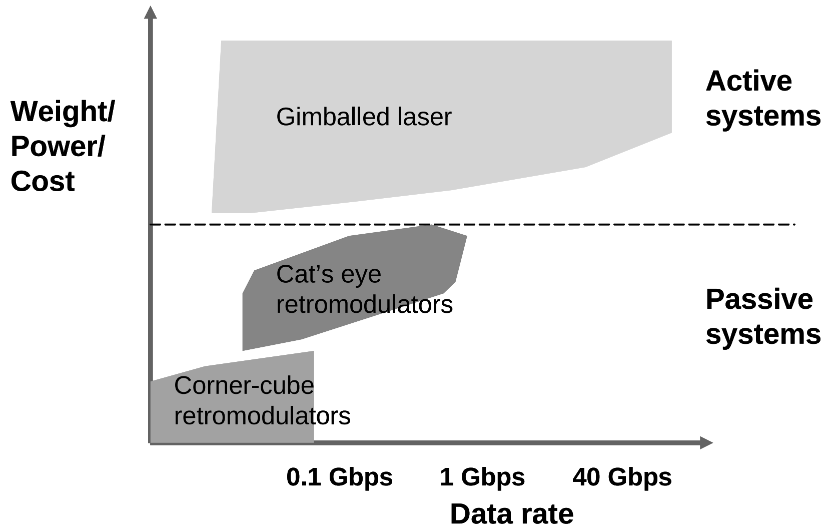


Figure 1. Approaches investigated by NRL for optical communications and tagging as a function of data rate.

2. FACILITIES

To conduct experiments in a maritime-environment, NRL has developed Free Space Optical (FSO) communications testbeds at the Chesapeake Bay Detachment (CBD) in Chesapeake Beach, MD. The facility enables on land and across-the-bay links. The west section of the testbed is located at Chesapeake Bay Detachment (CBD), and the east end is located at Tilghman Island (TI). Both locations are in Maryland, and they are separated by 16.2 km of water. A laser interrogator is located on a cliff about 30 meters above the beach. Depending on the applications active pointing can be used to acquire and track an object. A target board populated with retroreflectors and a beacon is located on a tower at TI. The target board is about 15 meters high so the propagation path across the bay has a slight negative slope.

The Transmitter/Receiver (Tx/Rx) site offers a bi-static geometry for the longer links where the transmitter is situated 0.5 m below the 40 cm telescope. The telescope itself is a gimbaled 40 cm Meade Schmidt-Cassegrain. The laser transmitter is a 1550 nm laser amplified to 2.5 W with an Erbium-Doped Fiber Amplifier. The output is coupled to a 10 cm collimating lens on a Sagebrush gimbal. Available detectors include InGaAs PIN-FETs, avalanche photodiodes, and fiber-coupled detectors that can support bandwidths up to 20 Gbps.

The target board is populated with two arrays of corner cube retroreflectors. One array has eleven 5 cm retroreflectors and one array has eleven 2.54 cm retroreflectors. A beacon provides a target for C_n^2 testing as well. A diagram of the site geometry is shown in Figure 2, as is a photo of the populated tower.

In addition to the bay testbed, there are meadows and piers available for static links as well as for UAV and shore-to-boat tests. These testbeds are typically monostatic to support the shorter ranges.

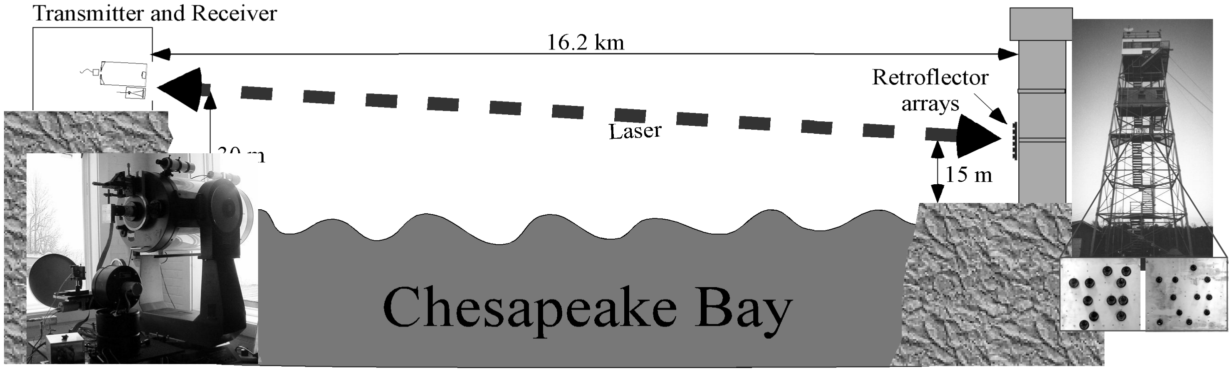


Figure 2. Geometry for 16.2 km links across Chesapeake Bay for laser links is shown. A photograph of tower on Tilghmann Island located across the bay is shown in the inset. The tower is populated with arrays of retroreflectors and with a beacon for C_n^2 measurements.

This facility is utilized for field-testing of optical components such as modulators and erbium doped fiber amplifiers (EDFA) developed and built at NRL along with commercially available components. In addition to supporting conventional "lasercom", the facility at CBD is used to investigate communication links with modulating retroreflectors. These links include ground-to-UAV and shore-to-ship links transferring real-time video and other data. Outside entities desiring a long FSO link to test their own equipment have collaborated with us in use of the Chesapeake Bay Lasercom Facility.

3. PROPAGATION CONDITIONS

Atmospheric conditions over bodies of water are different than for those over land masses. Typically, because the water is flat and the temperature is more constant, conditions can be more benign. However, turbulence still plays a major role in pointing and tracking, especially over multiple kilometers through horizontal paths. Even C_n^2 values on the order of 10^{-14} are challenging. More typical conditions of 10^{-13} and 10^{-12} are surprisingly problematic since ,to the eye, a day looks "clear". Figure 3 shows how turbulence affects seeing.

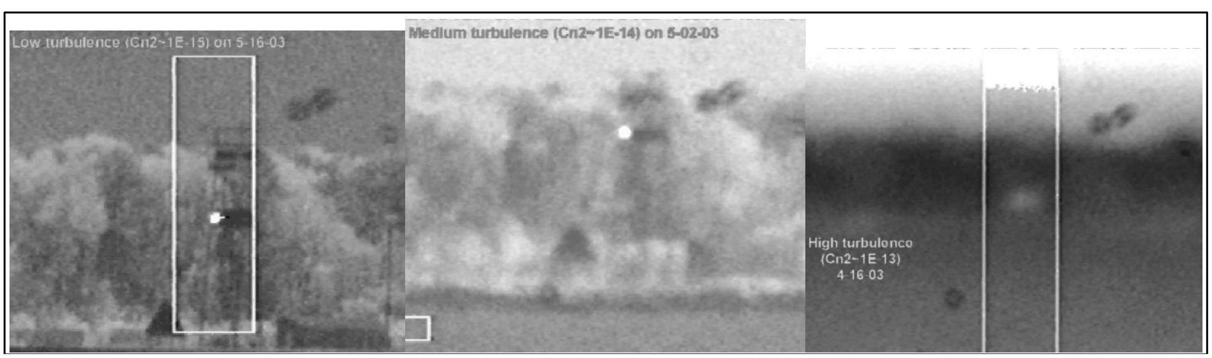


Figure 8: The Tilghman Island tower as imaged through the 5" diameter telescope is Figure 1 under 3 different levels of turbulence: a) low turbulence C_n^2~10^{-15} b) medium turbulence C_n^2~10^{-14} and c) high turbulence C_n^2~10^{-13}

NRL is approaching this problem by characterizing the values over long ranges with a new design for a low cost turbulence monitor [6]. This monitor, if successful, will enable us to measure the refractive index structure constant, C_n^2, over ranges that exceed a kilometer at a cost that promises to be 1/3 that of presently available commercial products

To characterize the channel typical of a maritime environment, we conducted tests sending a 1542 nm modulated laser beam, driven at 622 Mbps, across the bay, to be retroreflected by the array at TI. The bit error rate (BER) of the returned signal was measured and plotted as a function of time [7]. Some of these results are shown in Figure 4. From this Figure, we see that the BER gradually gets worse as the day progresses. This is likely due to the vertical temperature gradient that causes redirection of the beam out of the detector.

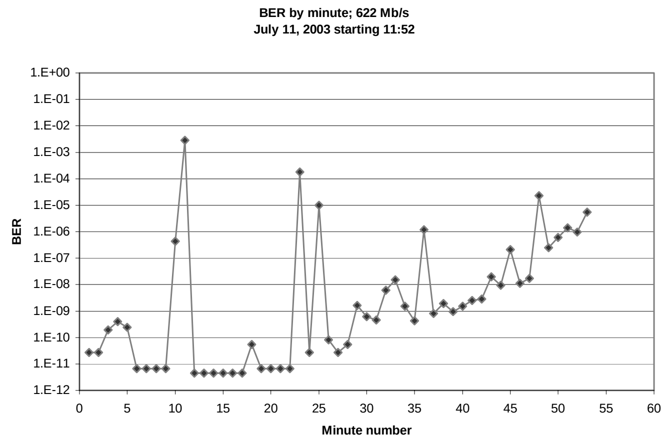
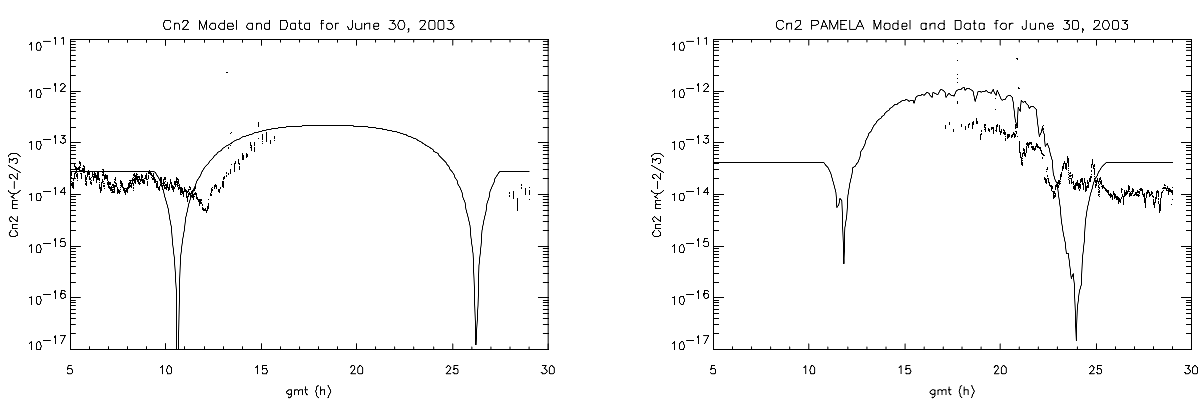


Figure 4: Results for BER Test 1 is shown. Note the gradual deterioriation of BER over time which is commensurate with temperature increases during the day.

To partially correct for this redirection and for beam wander in general, the pointing and tracking algorithms are being augmented with hardware using a fast steering mirror (FSM) combined with a position sensing detector (PSD) [8]. This combination enables better sustained coupling of the beam received at the Meade telescope into the fiber-coupled detector.

In addition to developing hardware to improve throughput, we are investigating adaptive detection thresholding as a method to correct for signal-dependent multiplicative noise[9]. This type of noise is characteristic of photodetectors with internal gain, like Avalanche Photodiodes (APDs). Analysis was verified with a simulated data sequence and real fade-rate data obtained over the 16.2 km link at the NRL FSO facility. These preliminary findings indicate that adaptive thresholding sampling at low frequencies may be implemented to improve BER in a free space optical link with significantly less intensive computational loads and commensurately lower costs. In future work, we will conduct experiments to verify these results.

To help us understand and predict how C_n^2 varies throughout the day in different climatic conditions, we are working with the Army and Air Force to develop a model which can be implemented in the field in standard applications like IDL, MatLab, etc. [10]. A sample of results comparing model to actual data taken at CBD and then the model modified by the data are shown in Figure 5. Work is ongoing in this area. It is a goal to provide a means in the field to get a quick look at how the C_n^2 values may vary for a given set of environmental conditions. With this knowledge, operational parameters can be modified to improve data link throughput.



(a) (b)

Figure 5(a) PAMELA model for Cn2 vs. time of day compared with data taken at CBD; (b) PAMELA model modified with real data

4. RETRO-DIVERSITY STUDIES

It is of interest to design arrays of retroreflectors for optimized signal return through the atmosphere. To determine useful architectures, we have been conducting experiments in "retro-diversity". For modulating retroreflector applications in particular, a compact array may not be the optimum architecture for best BER for a given set of C_n^2 values. The interference patterns generated from co-located retros illuminated by a coherent source combine with atmospheric effects to degrade system performance. In order to understand how to separate the effects of partial coherence and the atmosphere in a retromodulated link, we are conducing two different but related experiments.

Moore, et. al. [11], have been characterizing these effects over a 32.4 km link across the bay. The arrays on TI were illuminated by the 1550 nm laser and the retroreflected light from the array was received by the 16 inch Meade telescope. Images of the pupil plane are shown in Figure 6. These photos show the interference patterns from an array of twelve 5 cm corner cubes arranged in a 3x4 geometry. The retros were space on 12.5 cm centers. These results motivate a systematic study of retroreflector distribution which was conducted by Davidson, et. al.[12].

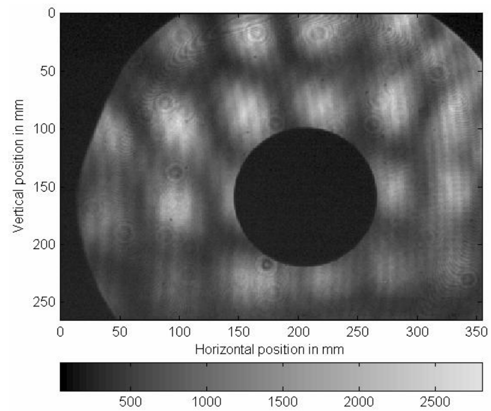


Figure 6. Interference pattern from reflection off four 5-cm diameter corner cubes mounted in an array on Tilghman Island.

In this work, intensity scintillation variances and intensity probability density functions (PDF) were experimentally measured for broad-band (2nm), 980 nm laser light reflected by two corner-cube retro-reflectors as a function of retro-reflector lateral spacing over a short (75 m) atmospheric optical path. The PDFs transitioned from broad double peaked "beta –shaped" densities to log-normal ones as the retro-reflector spacing was increased to exceed the optical field lateral coherence length. Specific spacing for a given average atmospheric refractive index structure constant C_n^2 eliminated coherent interference between light beams returned by each retro-reflector. An example of this transition is shown in Figure 7. In future work, we will repeat these experiments at 1550 nm.

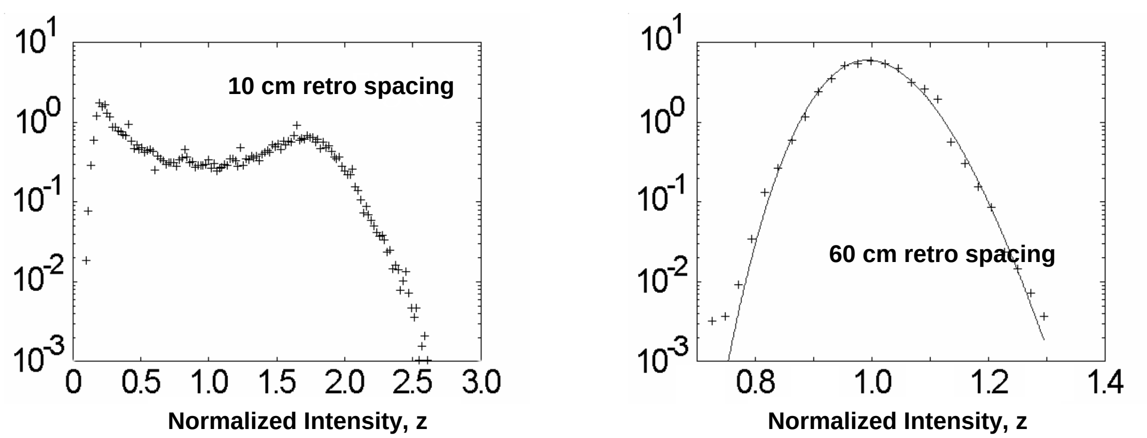


Figure 7. Migration from a saddle fit to a log-normal fit for increasing retroreflector spacing.

5. DEVICES & TECHNOLOGY

Progress in these field-based studies were able to be made because of the advancements in device design and technology developed at NRL for FSO links. For example, the lasers used in the eyesafe experiments made use of compact, lightweight, rugged high power lasers with EDFA amplifiers. These laser systems have an electrical-to-optical efficiency of 25%, and offer 2.5 W to 5 W of output laser power [13]. The amplifiers had the advantage of being able to amplify seed lasers within the Erbium band. This feature had specific relevance to the retromodulator projects as the MQW modulators "detune" when exposed to large changes in temperature. We were able to compensate for the shifts by using seed lasers of slightly different frequencies. Figure 8 shows a photo of one of the lasers used in the longer range links.

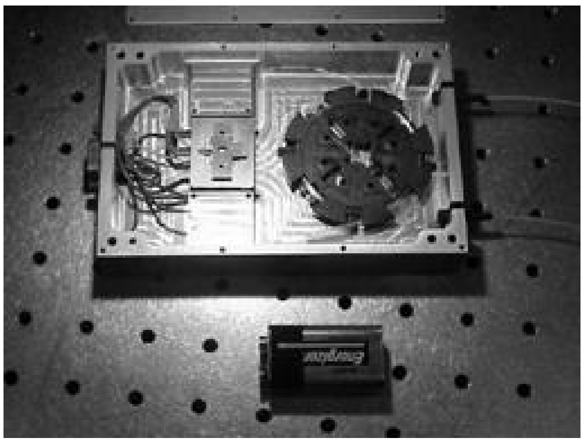


Figure 8. NRL 2.5 Watt 1.55 micron Fiber laser.

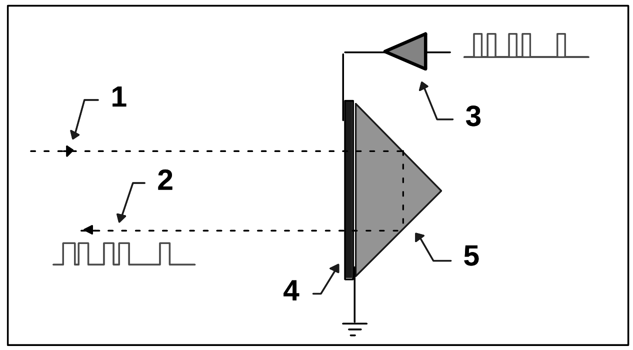


Figure 9. Concept for corner cube modulating retroreflector: 1) Interrogation Beam; 2) Modulated reflected beam; 3) Electronic driver; 4) Transmissive MQW modulator; 5) Solid corner cube retroreflector.

A significant thrust area has been in the development and implementation of multiple quantum well retromodulators [14]. NRL is investigating two classes of these types of devices. The first couples a corner cube optical retroreflector with an aperture matched transmissive MQW modulator (CCMRR). When a small amount of voltage is applied across the face of the modulator, the absorbance is shifted and the device acts like a shutter. Light is blocked or allowed to pass so on-off keying is enabled. The concept is illustrated in Figure 9. This type of device can support up to 10 Mbps for centimeter-scale apertures and is ideal for compact, low power applications where form factor and power loads must be nominal.

The second architecture under consideration is the Cats Eye retromodulator (CEMRR). This type of modulator is more complex and a bit more massive than the corner cube device but it promises to support data rates greater than 50 Mbps while consuming only tens of milliwatts of power. The MQW device is essentially a capacitance-limited device so the area determines speed. The focal-plane CEMRR under study by NRL places an array of small MQW shutters in the focal plane of optics designed to perform as a retroreflector. The small spot size (mm) enables fast data rates and the array combined with the optics keeps the aperture large enough to close realistic links. Details can be found in the literature [15].

In order to improve device performance, NRL investigators have borrowed from the solar cell community to design a grid contact approach [16]. These new designs for field distribution are showing significant improvement in response time compared to single ring designs. In addition to fabrication improvements, temperature-induced wavelength shifts are also being studied. High data rates heat the device and cause a shift in center frequency. This can impact the contrast ratio, hence signal-to-noise ratio when fielded. Lower drive voltages can mitigate this effect and are under aggressive study at the lab as well.

6. FIELD TESTS

The NRL has been demonstrating utility of its devices and techniques as they have emerged from the laboratory. Recent retromodulator tests have been conducted where a 1550 MQW retromodulator was placed on a fishing boat[16]. A small video camera fed its signal to a wavelet compression unit which drove the retromodulator at 3 Mbps with Reed-Solomon coding. The retromodulator was interrogated from shore using the 1550 nm FOS test bed. Realtime nearly continuous video was transmitted back to the interrogation site at 30 frames per second. Implications from this demonstration is that intelligence can be gathered remotely from the boat as well as on the boat and be transmitted to an interrogation location. Photos of the device and the compact optical transmit/receive optics are shown in Figure 10. A still from the video is shown in Figure 11.

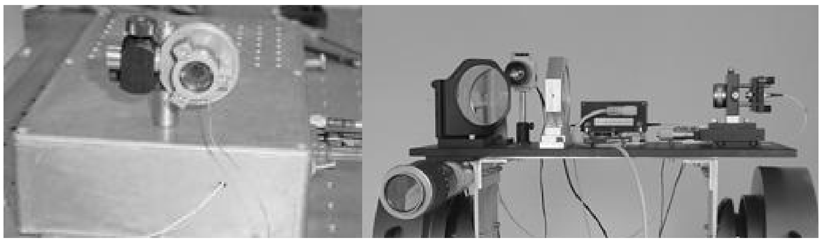


Figure10. Photo of the CCMRR used in the shore-to-boat efield test. Device was driven by a video signal at 3Mbps; Tx/Rx optics is shown on right.

Figure 11. Still from video taken in shore-to-boat MRR tests; Video was streamed in realtime at 30 fps.

In addition to the boat tests, we have recently successfully demonstrated real-time streaming video from a small UAV in flight at CBD using retromodulators. An array of five CCMRRs operating at 980 nm was mounted to a small model helicopter. A miniature video camera was also mounted to the helicopter and the signal was again compressed; the impedance matching circuitry drove the array a 3 Mbps. The helicopter flew above a meadow close to the water during the day. Ranges varied from 30 m to 120 m. Video was returned at 30 frames per second. During this test, radio control of the helicopter was lost and it crashed from about 120 meters. However, the array of retromodulators and the L3 compression unit were recovered and were undamaged. Photos of the helicopter before and after the flight are shown in Figure 12. Before and after data is shown in Figure 13.

7. CONCLUSIONS & FUTURE WORK

In this paper, we have presented a review of capabilities established at the Naval Research Laboratory in free space laser communications. Recently established test facilities at the Chesapeake Bay Detachment provide realistic maritime conditions for over-the-water and littoral tests. The free space optical program continues its efforts to develop technologies and techniques to propagate up to 40 Gbps over the water and through an atmosphere beset by strong turbulence. Retromodulator work continues and two recent field tests have shown the device’s utility for asymmetric communications for shore-to-boat and for realtime video streaming from a UAV.

In the upcoming year, we will continue to pursue retro-diversity experiments to separate out the effects of partial coherence from scintillation and turbulence. We will advance the Cats Eye Modulating Retroreflector and continue to demonstrate efficacy of using the corner cube device as a as a low power, small, lightweight communications terminal.

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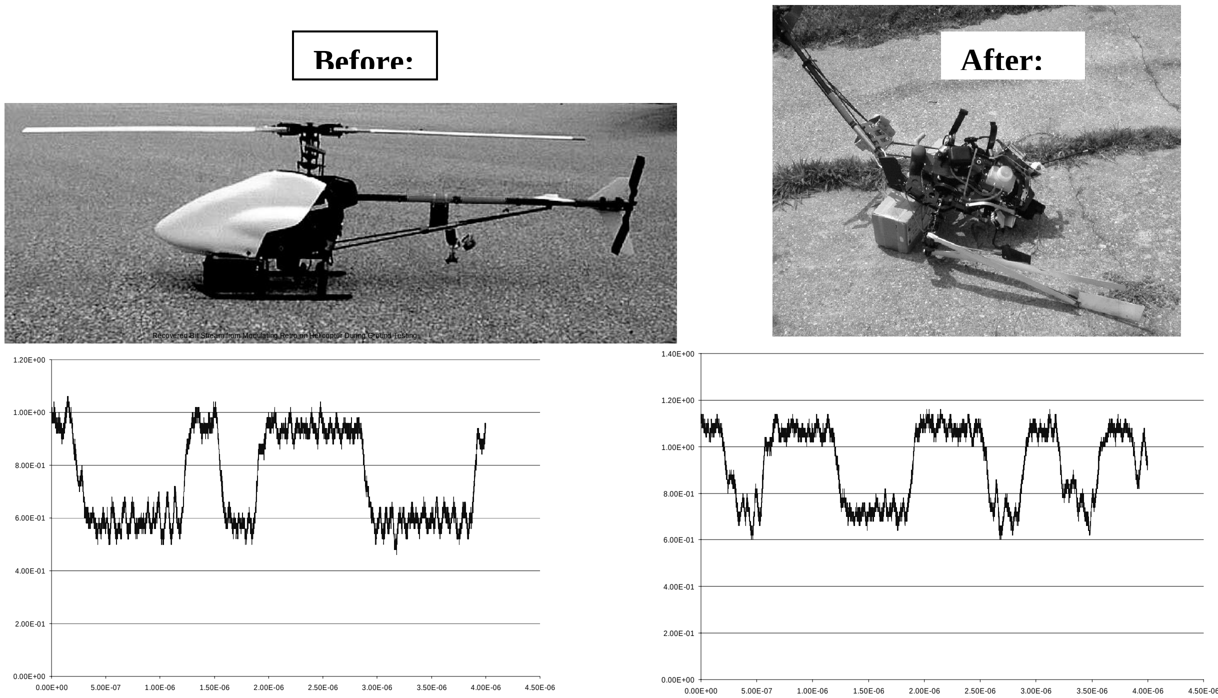

Figure 12. Helicopter and data before and after crash from 120 meters. Retromodulator array and L3 compression unit still functional!

REFERENCES

1. C.I. Moore, et. al., “Free-space high-speed laser communication link across the Chesapeake Bay”, *Proceedings of the SPIE.*, **4821**, pp. 474-485, 2002.

2. G.C. Gilbreath, et. al., “Progress in development of multiple quantum well retromodulators for free-space data links”, *Optical Engineering*, **42**(6), 1611-1617 (2003).

3. W.S. Rabinovich, et. al., “Free-space optical communications link at 1550 nm using multiple quantum well modulating retro-reflectors over a 1-kilometer range”, Opt.Soc.of Am Ann. Mtg., **230.5590**, May, 2003.

4. Michael J. Vilcheck, et.al., “Overview of the NCST’s New Optical Research Facility”, Proc. of the 2001 IEEE Aerospace Conference, **5.0496** (March, 2001).

5. M. J. Vilcheck, et. al., “Overview of the Naval Research Laboratory SLR Facility”, Proceedings of the 12th International Workshop on Laser Ranging, 13-17 November, 2000, Matera, Italy.

6. M. F. Stell, et. al., “Passive optical monitor for atmospheric turbulence and windspeed”, *Proceedings of the SPIE,* **This issue**, 2003.

7. M.J. Vilcheck, et. al. , “Progress in high-speed communication at the NRL Chesapeake Bay Lasercom Facility”, *Proceedings of the SPIE,* **This issue**, 2003.

8. M.R. Suite, et. al., “Fast steering mirror implementation for reduction of focal-spot wander in a long-distance free-space communication link”, *Proceedings of the SPIE,* **This issue**, 2003.

9. H. R. Burris, et. al., “Low Frequency Sampling Adaptive Thresholding for Free-Sapce Optical Communications Receivers with Multiplicative Noise”, *Proceedings of the SPIE*, **This issue**, 2003.

10. Eun Oh, et. al., “Optical Turbulence Model for Laser Propagation and Imaging Applications”, *Proceedings of the SPIE*, **This issue**, 2003.

11. Moore et. al. “Spatial intensity correlation and aperture averaging measurements in a 20 mile retro-reflected lasercom link”, *Proceedings of the SPIE*, **This issue**, 2003.

12. F. M. Davidson, et. al., “Scintillation Measurements of Broadband 980nm Laser Light in Clear Air Turbulence”**,** *Proceedings of the SPIE*, **This issue**, 2003.

13. J. Koplow, et. al.,. “A new method for side pumping of double-clad fiber sources”. *IEEE Journal of Quantum Electronics*, **39**(4), pp. 529-40 (2003).

14. http://mrr.nrl.navy.mil

15. Mark. L. Bierman, et. al, "Design and analysis of a diffraction limited cat's eye retroreflector", Opt. Eng., **41**(7), pp. 1655-1660 (2002).

16. Mahon et. al.“1550-nm 1-km maritime link at Chesapeake Beach”, *Proceedings of the SPIE*, **This issue**, 2003.